

CHAPTER

11

Multithreaded Programming

Java provides built-in support for *multithreaded programming*. A multithreaded program contains two or more parts that can run concurrently. Each part of such a program is called a *thread*, and each thread defines a separate path of execution. Thus, multithreading is a specialized form of multitasking.

You are almost certainly acquainted with multitasking because it is supported by virtually all modern operating systems. However, there are two distinct types of multitasking: process-based and thread-based. It is important to understand the difference between the two. For many readers, process-based multitasking is the more familiar form. A *process* is, in essence, a program that is executing. Thus, *process-based* multitasking is the feature that allows your computer to run two or more programs concurrently. For example, process-based multitasking enables you to run the Java compiler at the same time that you are using a text editor or visiting a web site. In process-based multitasking, a program is the smallest unit of code that can be dispatched by the scheduler.

In a *thread-based* multitasking environment, the thread is the smallest unit of dispatchable code. This means that a single program can perform two or more tasks simultaneously. For instance, a text editor can format text at the same time that it is printing, as long as these two actions are being performed by two separate threads. Thus, process-based multitasking deals with the “big picture,” and thread-based multitasking handles the details.

Multitasking threads require less overhead than multitasking processes. Processes are heavyweight tasks that require their own separate address spaces. Interprocess communication is expensive and limited. Context switching from one process to another is also costly. Threads, on the other hand, are lighter weight. They share the same address space and cooperatively share the same heavyweight process. Interthread communication is inexpensive, and context switching from one thread to the next is lower in cost. While Java programs make use of process-based multitasking environments, process-based multitasking is not under Java’s direct control. However, multithreaded multitasking is.

Multithreading enables you to write efficient programs that make maximum use of the processing power available in the system. One important way multithreading achieves this is by keeping idle time to a minimum. This is especially important for the interactive, networked

environment in which Java operates because **idle time is common**. For example, the transmission rate of data over a network is much slower than the rate at which the computer can process it. Even local file system resources are read and written at a much slower pace than they can be processed by the CPU. And, of course, user input is much slower than the computer. In a single-threaded environment, your program has to wait for each of these tasks to finish before it can proceed to the next one—even though most of the time the program is idle, waiting for input. Multithreading helps you reduce this idle time because another thread can run when one is waiting.

If you have programmed for operating systems such as **Windows**, then you are already familiar with **multithreaded programming**. However, the fact that Java manages threads makes multithreading especially convenient because many of the details are handled for you.

The Java Thread Model

The Java run-time system depends on **threads** for many things, and **all the class libraries** are **designed** with multithreading in mind. In fact, Java uses threads to enable the entire environment to be **asynchronous**. This helps **reduce inefficiency** by preventing the waste of CPU cycles.

The value of a multithreaded environment is best understood in **contrast** to its counterpart. **Single-threaded systems** use an approach called an **event loop** with **polling**. In this model, a single thread of **control** runs in an infinite loop, polling a single event queue to **decide what to do next**. Once this polling mechanism returns with, say, a signal that a **network file is ready to be read**, then the event loop **dispatches control** to the appropriate event handler. Until this event handler returns, **nothing else can happen** in the program. **This wastes CPU time**. It can also result in one part of a program **dominating** the system and **preventing any other events** from being processed. In general, in a single-threaded environment, when a **thread blocks** (that is, suspends execution) because it is waiting for some resource, the **entire program stops running**.

The **benefit** of Java's multithreading is that the **main loop/polling mechanism** is **eliminated**. One thread **can pause without stopping other parts** of your program. For example, the idle time created **when a thread reads data from a network** or waits for user input can be utilized elsewhere. Multithreading allows animation loops to sleep for a second between each frame **without causing the whole system to pause**. When a thread blocks in a Java program, **only the single thread that is blocked pauses**. All other threads **continue to run**.

As most readers know, over the past few years, multicore systems have become commonplace. Of course, single-core systems are still in widespread use. It is important to understand that Java's multithreading features work in both types of systems. In a single-core system, concurrently executing threads share the CPU, with each thread receiving a slice of CPU time. Therefore, in a single-core system, two or more threads do not actually run at the same time, but idle CPU time is utilized. However, in multicore systems, it is possible for two or more threads to actually execute simultaneously. In many cases, this can further improve program efficiency and increase the speed of certain operations.

NOTE In addition to the multithreading features described in this chapter, you will also want to explore the Fork/Join Framework. It provides a powerful means of creating multithreaded applications that automatically scale to make best use of multicore environments. The Fork/Join Framework is part of Java's support for *parallel programming*, which is the name commonly given to the techniques that optimize some types of algorithms for parallel execution in systems that have more than one CPU. For a discussion of the Fork/Join Framework and other concurrency utilities, see Chapter 29. Java's traditional multithreading capabilities are described here.

Threads exist in **several states**. Here is a general description. A thread can be **running**. It can be **ready to run** as soon as it gets CPU time. A running thread can be **suspended**, which temporarily halts its activity. A suspended thread can then be **resumed**, allowing it to pick up where it left off. A thread can be **blocked** when waiting for a resource. At any time, a thread can be **terminated**, which halts its execution immediately. Once terminated, a thread cannot be resumed.

Thread Priorities

Java assigns to each thread a **priority** that determines **how that thread should be treated** with respect to the others. Thread priorities are **integers** that specify the **relative priority** of one thread to another. As an absolute value, a priority is **meaningless**; a higher-priority thread **doesn't run any faster** than a lower-priority thread if it is the only thread running. Instead, a thread's priority is **used to decide when to switch** from one running thread to the next. This is called a **context switch**. The rules that determine when a context switch takes place are **simple**:

- *A thread can **voluntarily relinquish control**.* This occurs when explicitly **yielding**, **sleeping**, or when **blocked**. In this scenario, all other threads are examined, and the **highest-priority thread** that is **ready to run** is given the CPU.
- *A thread can be **preempted by a higher-priority thread**.* In this case, a lower-priority thread that **does not yield the processor** is simply **preempted**—no matter what it is doing—by a higher-priority thread. Basically, as soon as a higher-priority thread wants to run, it does. This is called **preemptive multitasking**.

In cases where two threads with the same priority are competing for CPU cycles, the situation is a bit complicated. For some operating systems, threads of equal priority are time-sliced automatically in round-robin fashion. For other types of operating systems, threads of equal priority must voluntarily yield control to their peers. If they don't, the other threads will not run.

CAUTION Portability problems can arise from the differences in the way that operating systems context-switch threads of equal priority.

Synchronization

Because multithreading introduces an **asynchronous behavior** to your programs, there must be a way for you to **enforce synchronicity** when you need it. For example, if you want two threads to **communicate** and share a complicated data structure, such as a linked list, you need some way to ensure that **they don't conflict with each other**. That is, you must **prevent** one thread

from writing data while another thread is in the middle of reading it. For this purpose, Java implements an elegant twist on an age-old model of interprocess synchronization: the *monitor*. The monitor is a control mechanism first defined by C.A.R. Hoare. You can think of a monitor as a very small box that can hold only one thread. Once a thread enters a monitor, all other threads must wait until that thread exits the monitor. In this way, a monitor can be used to protect a shared asset from being manipulated by more than one thread at a time.

In Java, there is no class “Monitor”; instead, each object has its own implicit monitor that is automatically entered when one of the object’s synchronized methods is called. Once a thread is inside a synchronized method, no other thread can call any other synchronized method on the same object. This enables you to write very clear and concise multithreaded code, because synchronization support is built into the language.

Messaging

After you divide your program into separate threads, you need to define how they will communicate with each other. When programming with some other languages, you must depend on the operating system to establish communication between threads. This, of course, adds overhead. By contrast, Java provides a clean, low-cost way for two or more threads to talk to each other, via calls to predefined methods that all objects have. Java’s messaging system allows a thread to enter a synchronized method on an object, and then wait there until some other thread explicitly notifies it to come out.

The Thread Class and the Runnable Interface

Java’s multithreading system is built upon the Thread class, its methods, and its companion interface, Runnable. Thread encapsulates a thread of execution. Since you can’t directly refer to the ethereal state of a running thread, you will deal with it through its proxy, the Thread instance that spawned it. To create a new thread, your program will either extend Thread or implement the Runnable interface.

The Thread class defines several methods that help manage threads. Several of those used in this chapter are shown here:

Method	Meaning
getName	Obtain a thread’s name.
getPriority	Obtain a thread’s priority.
isAlive	Determine if a thread is still running.
join	Wait for a thread to terminate.
run	Entry point for the thread.
sleep	Suspend a thread for a period of time.
start	Start a thread by calling its run method.

Thus far, all the examples in this book have used a single thread of execution. The remainder of this chapter explains how to use Thread and Runnable to create and manage threads, beginning with the one thread that all Java programs have: the main thread.

The Main Thread

When a Java program starts up, one thread begins running immediately. This is usually called the **main thread** of your program, because it is the one that is **executed** when your program begins. The main thread is important for **two reasons**:

- It is the thread from which other “child” threads will be **spawned**.
- Often, it must be the **last thread to finish execution** because it performs various shutdown actions.

Although the main thread is **created automatically** when your program is started, it can be **controlled** through a **Thread** object. To do so, you must obtain a **reference** to it by calling the method **currentThread()**, which is a **public static** member of **Thread**. Its general form is shown here:

```
static Thread currentThread()
```

This method returns a **reference** to the thread in which it is called. Once you have a **reference** to the main thread, you can control it **just like any other thread**.

Let’s begin by reviewing the following example:

```
// Controlling the main Thread.
class CurrentThreadDemo {
    public static void main(String[] args) {
        Thread t = Thread.currentThread();

        System.out.println("Current thread: " + t);

        // change the name of the thread
        t.setName("My Thread");
        System.out.println("After name change: " + t);

        try {
            for(int n = 5; n > 0; n--) {
                System.out.println(n);
                Thread.sleep(1000);
            }
        } catch (InterruptedException e) {
            System.out.println("Main thread interrupted");
        }
    }
}
```

In this program, a **reference** to the current thread (the main thread, in this case) is obtained by calling **currentThread()**, and this reference is stored in the **local variable t**. Next, the program displays information about the thread. The program then calls **setName()** to change the **internal name of the thread**. Information about the thread is then redisplayed. Next, a loop counts down from five, pausing **one second** between each line. The pause is accomplished by the **sleep()** method. The argument to **sleep()** specifies the delay period in **milliseconds**. Notice the **try/catch** block around this loop. The **sleep()** method in **Thread** might throw an **InterruptedException**. This would happen if some other thread wanted

to interrupt this sleeping one. This example just prints a message if it gets interrupted. In a real program, you would need to handle this differently. Here is the output generated by this program:

```
Current thread: Thread [main, 5, main]
After name change: Thread [My Thread, 5, main]
5
4
3
2
1
```

Notice the output produced when `t` is used as an argument to `println()`. This displays, in order: the name of the thread, its priority, and the name of its group. By default, the name of the main thread is `main`. Its priority is 5, which is the default value, and `main` is also the name of the group of threads to which this thread belongs. A *thread group* is a data structure that controls the state of a collection of threads as a whole. After the name of the thread is changed, `t` is again output. This time, the new name of the thread is displayed.

Let's look more closely at the methods defined by `Thread` that are used in the program. The `sleep()` method causes the thread from which it is called to suspend execution for the specified period of milliseconds. Its general form is shown here:

```
static void sleep(long milliseconds) throws InterruptedException
```

The number of milliseconds to suspend is specified in *milliseconds*. This method may throw an `InterruptedException`.

The `sleep()` method has a second form, shown next, which allows you to specify the period in terms of milliseconds and nanoseconds:

```
static void sleep(long milliseconds, int nanoseconds) throws InterruptedException
```

This second form is useful only in environments that allow timing periods as short as nanoseconds.

As the preceding program shows, you can set the name of a thread by using `setName()`. You can obtain the name of a thread by calling `getName()` (but note that this is not shown in the program). These methods are members of the `Thread` class and are declared like this:

```
final void setName(String threadName)
final String getName()
```

Here, *threadName* specifies the name of the thread.

Creating a Thread

In the most general sense, you create a thread by instantiating an object of type `Thread`. Java defines two ways in which this can be accomplished:

- You can implement the `Runnable` interface.
- You can extend the `Thread` class, itself.

The following two sections look at each method, in turn.

Implementing Runnable

The easiest way to create a thread is to create a class that implements the **Runnable** interface. **Runnable** abstracts a unit of executable code. You can construct a thread on any object that implements **Runnable**. To implement **Runnable**, a class need only implement a single method called **run()**, which is declared like this:

```
public void run()
```

Inside **run()**, you will define the code that constitutes the new thread. It is important to understand that **run()** can call other methods, use other classes, and declare variables, just like the main thread can. The only difference is that **run()** establishes the entry point for another, concurrent thread of execution within your program. This thread will end when **run()** returns.

After you create a class that implements **Runnable**, you will instantiate an object of type **Thread** from within that class. **Thread** defines several constructors. The one that we will use is shown here:

```
Thread(Runnable threadOb, String threadName)
```

In this constructor, *threadOb* is an instance of a class that implements the **Runnable** interface. This defines where execution of the thread will begin. The name of the new thread is specified by *threadName*.

After the new thread is created, it will not start running until you call its **start()** method, which is declared within **Thread**. In essence, **start()** initiates a call to **run()**. The **start()** method is shown here:

```
void start()
```

Here is an example that creates a new thread and starts it running:

```
// Create a second thread.
class NewThread implements Runnable {
    Thread t;

    NewThread() {
        // Create a new, second thread
        t = new Thread(this, "Demo Thread");
        System.out.println("Child thread: " + t);
    }

    // This is the entry point for the second thread.
    public void run() {
        try {
            for(int i = 5; i > 0; i--) {
                System.out.println("Child Thread: " + i);
                Thread.sleep(500);
            }
        } catch (InterruptedException e) {
            System.out.println("Child interrupted.");
        }
        System.out.println("Exiting child thread.");
    }
}
```

```

class ThreadDemo {
    public static void main(String[] args) {
        NewThread nt = new NewThread(); // create a new thread

        nt.t.start(); // Start the thread

        try {
            for(int i = 5; i > 0; i--) {
                System.out.println("Main Thread: " + i);
                Thread.sleep(1000);
            }
        } catch (InterruptedException e) {
            System.out.println("Main thread interrupted.");
        }
        System.out.println("Main thread exiting.");
    }
}

```

Inside **NewThread**'s constructor, a new **Thread** object is created by the following statement:

```
t = new Thread(this, "Demo Thread");
```

Passing **this** as the first argument indicates that you want the new thread to call the **run()** method on **this** object. Inside **main()**, **start()** is called, which starts the thread of execution beginning at the **run()** method. This causes the child thread's **for** loop to begin. Next the main thread enters its **for** loop. Both threads continue running, sharing the CPU in single-core systems, until their loops finish. The output produced by this program is as follows. (Your output may vary based upon the specific execution environment.)

```

Child thread: Thread[Demo Thread,5,main]
Main Thread: 5
Child Thread: 5
Child Thread: 4
Main Thread: 4
Child Thread: 3
Child Thread: 2
Main Thread: 3
Child Thread: 1
Exiting child thread.
Main Thread: 2
Main Thread: 1
Main thread exiting.

```

As mentioned earlier, in a multithreaded program, it is often useful for the main thread to be the last thread to finish running. The preceding program ensures that the main thread finishes last, because the main thread sleeps for 1,000 milliseconds between iterations, but the child thread sleeps for only 500 milliseconds. This causes the child thread to terminate earlier than the main thread. Shortly, you will see a better way to wait for a thread to finish.

Extending Thread

The second way to create a thread is to create a **new class** that extends **Thread**, and then to create an instance of that class. The **extending** class must override the **run()** method, which is the entry point for the new thread. As before, a call to **start()** begins execution of the new thread. Here is the preceding program rewritten to extend **Thread**:

```
// Create a second thread by extending Thread
class NewThread extends Thread {

    NewThread() {
        // Create a new, second thread
        super("Demo Thread");
        System.out.println("Child thread: " + this);
    }

    // This is the entry point for the second thread.
    public void run() {
        try {
            for(int i = 5; i > 0; i--) {
                System.out.println("Child Thread: " + i);
                Thread.sleep(500);
            }
        } catch (InterruptedException e) {
            System.out.println("Child interrupted.");
        }
        System.out.println("Exiting child thread.");
    }
}

class ExtendThread {
    public static void main(String[] args) {
        NewThread nt = new NewThread(); // create a new thread

        nt.start(); // start the thread

        try {
            for(int i = 5; i > 0; i--) {
                System.out.println("Main Thread: " + i);
                Thread.sleep(1000);
            }
        } catch (InterruptedException e) {
            System.out.println("Main thread interrupted.");
        }
        System.out.println("Main thread exiting.");
    }
}
```

This program generates the same output as the preceding version. As you can see, the child thread is created by instantiating an object of **NewThread**, which is derived from **Thread**.

Notice the call to `super()` inside `NewThread`. This invokes the following form of the `Thread` constructor:

```
public Thread(String threadName)
```

Here, `threadName` specifies the name of the thread.

Choosing an Approach

At this point, you might be wondering why Java has two ways to create child threads, and which approach is better. The answers to these questions turn on the same point. The `Thread` class defines several methods that can be overridden by a derived class. Of these methods, the only one that must be overridden is `run()`. This is, of course, the same method required when you implement `Runnable`. Many Java programmers feel that classes should be extended only when they are being enhanced or adapted in some way. So, if you will not be overriding any of `Thread`'s other methods, it is probably best simply to implement `Runnable`. Also, by implementing `Runnable`, your thread class does not need to inherit `Thread`, making it free to inherit a different class. Ultimately, which approach to use is up to you. However, throughout the rest of this chapter, we will create threads by using classes that implement `Runnable`.

Creating Multiple Threads

So far, you have been using only two threads: the main thread and one child thread. However, your program can spawn as many threads as it needs. For example, the following program creates three child threads:

```
// Create multiple threads.
class NewThread implements Runnable {
    String name; // name of thread
    Thread t;

    NewThread(String threadname) {
        name = threadname;
        t = new Thread(this, name);
        System.out.println("New thread: " + t);
    }

    // This is the entry point for thread.
    public void run() {
        try {
            for(int i = 5; i > 0; i--) {
                System.out.println(name + ": " + i);
                Thread.sleep(1000);
            }
        } catch (InterruptedException e) {
            System.out.println(name + "Interrupted");
        }
        System.out.println(name + " exiting.");
    }
}
```

```
class MultiThreadDemo {
    public static void main(String[] args) {
        NewThread nt1 = new NewThread("One");
        NewThread nt2 = new NewThread("Two");
        NewThread nt3 = new NewThread("Three");

        // Start the threads.
        nt1.t.start();
        nt2.t.start();
        nt3.t.start();

        try {
            // wait for other threads to end
            Thread.sleep(10000);
        } catch (InterruptedException e) {
            System.out.println("Main thread Interrupted");
        }

        System.out.println("Main thread exiting.");
    }
}
```

Sample output from this program is shown here. (Your output may vary based upon the specific execution environment.)

```
New thread: Thread[One,5,main]
New thread: Thread[Two,5,main]
New thread: Thread[Three,5,main]
One: 5
Two: 5
Three: 5
One: 4
Two: 4
Three: 4
One: 3
Three: 3
Two: 3
One: 2
Three: 2
Two: 2
One: 1
Three: 1
Two: 1
One exiting.
Two exiting.
Three exiting.
Main thread exiting.
```

As you can see, once started, all three child threads share the CPU. Notice the call to **sleep(10000)** in **main()**. This causes the main thread to sleep for ten seconds and ensures that it will finish last.

Using `isAlive()` and `join()`

As mentioned, often you will want the main thread to finish last. In the preceding examples, this is accomplished by calling `sleep()` within `main()`, with a long enough delay to ensure that all child threads terminate prior to the main thread. However, this is hardly a satisfactory solution, and it also raises a larger question: How can one thread know when another thread has ended? Fortunately, **Thread** provides a means by which you can answer this question.

Two ways exist to determine whether a thread has finished. First, you can call `isAlive()` on the thread. This method is defined by **Thread**, and its general form is shown here:

```
final boolean isAlive()
```

The `isAlive()` method returns **true** if the thread upon which it is called is still running. It returns **false** otherwise.

While `isAlive()` is occasionally useful, the method that you will more commonly use to wait for a thread to finish is called `join()`, shown here:

```
final void join() throws InterruptedException
```

This method waits until the thread on which it is called terminates. Its name comes from the concept of the calling thread waiting until the specified thread *joins* it. Additional forms of `join()` allow you to specify a maximum amount of time that you want to wait for the specified thread to terminate.

Here is an improved version of the preceding example that uses `join()` to ensure that the main thread is the last to stop. It also demonstrates the `isAlive()` method.

```
// Using join() to wait for threads to finish.
class NewThread implements Runnable {
    String name; // name of thread
    Thread t;

    NewThread(String threadname) {
        name = threadname;
        t = new Thread(this, name);
        System.out.println("New thread: " + t);
    }

    // This is the entry point for thread.
    public void run() {
        try {
            for(int i = 5; i > 0; i--) {
                System.out.println(name + ": " + i);
                Thread.sleep(1000);
            }
        } catch (InterruptedException e) {
            System.out.println(name + " interrupted.");
        }
        System.out.println(name + " exiting.");
    }
}
```

```

class DemoJoin {
    public static void main(String[] args) {
        NewThread nt1 = new NewThread("One");
        NewThread nt2 = new NewThread("Two");
        NewThread nt3 = new NewThread("Three");

        // Start the threads.
        nt1.t.start();
        nt2.t.start();
        nt3.t.start();

        System.out.println("Thread One is alive: "
            + nt1.t.isAlive());
        System.out.println("Thread Two is alive: "
            + nt2.t.isAlive());
        System.out.println("Thread Three is alive: "
            + nt3.t.isAlive());
        // wait for threads to finish
        try {
            System.out.println("Waiting for threads to finish.");
            nt1.t.join();
            nt2.t.join();
            nt3.t.join();
        } catch (InterruptedException e) {
            System.out.println("Main thread Interrupted");
        }

        System.out.println("Thread One is alive: "
            + nt1.t.isAlive());
        System.out.println("Thread Two is alive: "
            + nt2.t.isAlive());
        System.out.println("Thread Three is alive: "
            + nt3.t.isAlive());

        System.out.println("Main thread exiting.");
    }
}

```

Sample output from this program is shown here. (Your output may vary based upon the specific execution environment.)

```

New thread: Thread[One,5,main]
New thread: Thread[Two,5,main]
New thread: Thread[Three,5,main]
Thread One is alive: true
Thread Two is alive: true
Thread Three is alive: true
Waiting for threads to finish.
One: 5
Two: 5
Three: 5
One: 4
Two: 4
Three: 4

```

```

One: 3
Two: 3
Three: 3
One: 2
Two: 2
Three: 2
One: 1
Two: 1
Three: 1
Two exiting.
Three exiting.
One exiting.
Thread One is alive: false
Thread Two is alive: false
Thread Three is alive: false
Main thread exiting.

```

As you can see, after the calls to `join()` return, the threads have stopped executing.

Thread Priorities

Thread priorities are used by the thread scheduler to decide when each thread should be allowed to run. In theory, over a given period of time, higher-priority threads get more CPU time than lower-priority threads. In practice, the amount of CPU time that a thread gets often depends on several factors besides its priority. (For example, how an operating system implements multitasking can affect the relative availability of CPU time.) A higher-priority thread can also preempt a lower-priority one. For instance, when a lower-priority thread is running and a higher-priority thread resumes (from sleeping or waiting on I/O, for example), it will preempt the lower-priority thread.

In theory, threads of equal priority should get equal access to the CPU. But you need to be careful. Remember, Java is designed to work in a wide range of environments. Some of those environments implement multitasking fundamentally differently than others. For safety, threads that share the same priority should yield control once in a while. This ensures that all threads have a chance to run under a nonpreemptive operating system. In practice, even in nonpreemptive environments, most threads still get a chance to run, because most threads inevitably encounter some blocking situation, such as waiting for I/O. When this happens, the blocked thread is suspended and other threads can run. But, if you want smooth multithreaded execution, you are better off not relying on this. Also, some types of tasks are CPU-intensive. Such threads dominate the CPU. For these types of threads, you want to yield control occasionally so that other threads can run.

To set a thread's priority, use the `setPriority()` method, which is a member of **Thread**. This is its general form:

```
final void setPriority(int level)
```

Here, *level* specifies the new priority setting for the calling thread. The value of *level* must be within the range `MIN_PRIORITY` and `MAX_PRIORITY`. Currently, these values are 1 and

10, respectively. To return a thread to default priority, specify **NORM_PRIORITY**, which is currently 5. These priorities are defined as **static final** variables within **Thread**.

You can obtain the current priority setting by calling the **getPriority()** method of **Thread**, shown here:

```
final int getPriority()
```

Implementations of Java may have radically different behavior when it comes to scheduling. Most of the inconsistencies arise when you have threads that are relying on preemptive behavior, instead of cooperatively giving up CPU time. The safest way to obtain predictable, cross-platform behavior with Java is to use threads that voluntarily give up control of the CPU.

Synchronization

When two or more threads need access to a shared resource, they need some way to ensure that the resource will be used by only one thread at a time. The process by which this is achieved is called *synchronization*. As you will see, Java provides unique, language-level support for it.

Key to synchronization is the concept of the monitor. A *monitor* is an object that is used as a mutually exclusive lock. Only one thread can *own* a monitor at a given time. When a thread acquires a lock, it is said to have *entered* the monitor. All other threads attempting to enter the locked monitor will be suspended until the first thread *exits* the monitor. These other threads are said to be *waiting* for the monitor. A thread that owns a monitor can reenter the same monitor if it so desires.

You can synchronize your code in either of two ways. Both involve the use of the **synchronized** keyword, and both are examined here.

Using Synchronized Methods

Synchronization is easy in Java, because all objects have their own implicit monitor associated with them. To enter an object's monitor, just call a method that has been modified with the **synchronized** keyword. While a thread is inside a synchronized method, all other threads that try to call it (or any other synchronized method) on the same instance have to wait. To exit the monitor and relinquish control of the object to the next waiting thread, the owner of the monitor simply returns from the synchronized method.

To understand the need for synchronization, let's begin with a simple example that does not use it—but should. The following program has three simple classes. The first one, **Callme**, has a single method named **call()**. The **call()** method takes a **String** parameter called **msg**. This method tries to print the **msg** string inside of square brackets. The interesting thing to notice is that after **call()** prints the opening bracket and the **msg** string, it calls **Thread.sleep(1000)**, which pauses the current thread for one second.

The constructor of the next class, **Caller**, takes a reference to an instance of the **Callme** class and a **String**, which are stored in **target** and **msg**, respectively. The constructor also creates a new thread that will call this object's **run()** method. The **run()** method of **Caller** calls the **call()** method on the **target** instance of **Callme**, passing in the **msg** string. Finally, the **Synch** class starts by creating a single instance of **Callme**, and three instances

of **Caller**, each with a unique message string. The same instance of **Callme** is passed to each **Caller**.

```
// This program is not synchronized.
class Callme {
    void call(String msg) {
        System.out.print "[" + msg);
        try {
            Thread.sleep(1000);
        } catch (InterruptedException e) {
            System.out.println("Interrupted");
        }
        System.out.println("]");
    }
}

class Caller implements Runnable {
    String msg;
    Callme target;
    Thread t;

    public Caller(Callme targ, String s) {
        target = targ;
        msg = s;
        t = new Thread(this);
    }

    public void run() {
        target.call(msg);
    }
}

class Synch {
    public static void main(String[] args) {
        Callme target = new Callme();
        Caller ob1 = new Caller(target, "Hello");
        Caller ob2 = new Caller(target, "Synchronized");
        Caller ob3 = new Caller(target, "World");

        // Start the threads.
        ob1.t.start();
        ob2.t.start();
        ob3.t.start();

        // wait for threads to end
        try {
            ob1.t.join();
            ob2.t.join();
            ob3.t.join();
        } catch (InterruptedException e) {
            System.out.println("Interrupted");
        }
    }
}
```


Here is the output produced by this program:

```
[Hello[Synchronized[World]
]
]
```

As you can see, by calling **sleep()**, the **call()** method allows execution to switch to another thread. This results in the mixed-up output of the three message strings. In this program, nothing exists to stop all three threads from calling the same method, on the same object, at the same time. This is known as a *race condition*, because the three threads are racing each other to complete the method. This example used **sleep()** to make the effects repeatable and obvious. In most situations, a race condition is more subtle and less predictable, because you can't be sure when the context switch will occur. This can cause a program to run right one time and wrong the next.

To fix the preceding program, you must *serialize* access to **call()**. That is, you must restrict its access to only one thread at a time. To do this, you simply need to precede **call()**'s definition with the keyword **synchronized**, as shown here:

```
class Callme {
    synchronized void call(String msg) {
        ...
    }
}
```

This prevents other threads from entering **call()** while another thread is using it. After **synchronized** has been added to **call()**, the output of the program is as follows:

```
[Hello]
[Synchronized]
[World]
```

Any time that you have a method, or group of methods, that manipulates the internal state of an object in a multithreaded situation, you should use the **synchronized** keyword to guard the state from race conditions. Remember, once a thread enters any synchronized method on an instance, no other thread can enter any other synchronized method on the same instance. However, nonsynchronized methods on that instance will continue to be callable.

The **synchronized** Statement

While creating **synchronized** methods within classes that you create is an easy and effective means of achieving synchronization, it will not work in all cases. To understand why, consider the following. Imagine that you want to synchronize access to objects of a class that was not designed for multithreaded access. That is, the class does not use **synchronized** methods. Further, this class was not created by you, but by a third party, and you do not have access to the source code. Thus, you can't add **synchronized** to the appropriate methods within the class. How can access to an object of this class be synchronized? Fortunately, the solution to this problem is quite easy: You simply put calls to the methods defined by this class inside a **synchronized** block.

This is the general form of the **synchronized** statement:

```
synchronized(objRef) {
    // statements to be synchronized
}
```

Here, *objRef* is a reference to the object being synchronized. A synchronized block ensures that a call to a synchronized method that is a member of *objRef*'s class occurs only after the current thread has successfully entered *objRef*'s monitor.

Here is an alternative version of the preceding example, using a synchronized block within the **run()** method:

```
// This program uses a synchronized block.
class Callme {
    void call(String msg) {
        System.out.print "[" + msg);
        try {
            Thread.sleep(1000);
        } catch (InterruptedException e) {
            System.out.println("Interrupted");
        }
        System.out.println("]");
    }
}

class Caller implements Runnable {
    String msg;
    Callme target;
    Thread t;

    public Caller(Callme targ, String s) {
        target = targ;
        msg = s;
        t = new Thread(this);
    }

    // synchronize calls to call()
    public void run() {
        synchronized(target) { // synchronized block
            target.call(msg);
        }
    }
}

class Synch1 {
    public static void main(String[] args) {
        Callme target = new Callme();
        Caller ob1 = new Caller(target, "Hello");
        Caller ob2 = new Caller(target, "Synchronized");
        Caller ob3 = new Caller(target, "World");
    }
}
```

```
// Start the threads.
ob1.t.start();
ob2.t.start();
ob3.t.start();

// wait for threads to end
try {
    ob1.t.join();
    ob2.t.join();
    ob3.t.join();
} catch (InterruptedException e) {
    System.out.println("Interrupted");
}
}
```

Here, the `call()` method is not modified by **synchronized**. Instead, the **synchronized** statement is used inside **Caller's run()** method. This causes the same correct output as the preceding example, because each thread waits for the prior one to finish before proceeding.

Interthread Communication

The preceding examples unconditionally blocked other threads from asynchronous access to certain methods. This use of the implicit monitors in Java objects is powerful, but you can achieve a more subtle level of control through interprocess communication. As you will see, this is especially easy in Java.

As discussed earlier, multithreading replaces event loop programming by dividing your tasks into discrete, logical units. Threads also provide a secondary benefit: they do away with polling. Polling is usually implemented by a loop that is used to check some condition repeatedly. Once the condition is true, appropriate action is taken. This wastes CPU time. For example, consider the classic queuing problem, where one thread is producing some data and another is consuming it. To make the problem more interesting, suppose that the producer has to wait until the consumer is finished before it generates more data. In a polling system, the consumer would waste many CPU cycles while it waited for the producer to produce. Once the producer was finished, it would start polling, wasting more CPU cycles waiting for the consumer to finish, and so on. Clearly, this situation is undesirable.

To avoid polling, Java includes an elegant interprocess communication mechanism via the `wait()`, `notify()`, and `notifyAll()` methods. These methods are implemented as **final** methods in **Object**, so all classes have them. All three methods can be called only from within a **synchronized** context. Although conceptually advanced from a computer science perspective, the rules for using these methods are actually quite simple:

- **wait()** tells the calling thread to give up the monitor and go to sleep until some other thread enters the same monitor and calls **notify()** or **notifyAll()**.
- **notify()** wakes up a thread that called **wait()** on the same object.
- **notifyAll()** wakes up all the threads that called **wait()** on the same object. One of the threads will be granted access.

These methods are declared within **Object**, as shown here:

```
final void wait( ) throws InterruptedException
final void notify( )
final void notify All( )
```

Additional forms of **wait()** exist that allow you to specify a period of time to wait.

Before working through an example that illustrates interthread communication, an important point needs to be made. Although **wait()** normally waits until **notify()** or **notifyAll()** is called, there is a possibility that in very rare cases the waiting thread could be awakened due to a *spurious wakeup*. In this case, a waiting thread resumes without **notify()** or **notifyAll()** having been called. (In essence, the thread resumes for no apparent reason.) Because of this remote possibility, the Java API documentation recommends that calls to **wait()** should take place within a loop that checks the condition on which the thread is waiting. The following example shows this technique.

Let's now work through an example that uses **wait()** and **notify()**. To begin, consider the following sample program that incorrectly implements a simple form of the producer/consumer problem. It consists of four classes: **Q**, the queue that you're trying to synchronize; **Producer**, the threaded object that is producing queue entries; **Consumer**, the threaded object that is consuming queue entries; and **PC**, the tiny class that creates the single **Q**, **Producer**, and **Consumer**.

```
// An incorrect implementation of a producer and consumer.
class Q {
    int n;

    synchronized int get() {
        System.out.println("Got: " + n);
        return n;
    }

    synchronized void put(int n) {
        this.n = n;
        System.out.println("Put: " + n);
    }
}

class Producer implements Runnable {
    Q q;
    Thread t;

    Producer(Q q) {
        this.q = q;
        t = new Thread(this, "Producer");
    }

    public void run() {
        int i = 0;

        while(true) {
            q.put(i++);
        }
    }
}
```

```

    }
}

class Consumer implements Runnable {
    Q q;
    Thread t;

    Consumer(Q q) {
        this.q = q;
        t = new Thread(this, "Consumer");
    }

    public void run() {
        while(true) {
            q.get();
        }
    }
}

class PC {
    public static void main(String[] args) {
        Q q = new Q();
        Producer p = new Producer(q);
        Consumer c = new Consumer(q);

        // Start the threads.
        p.t.start();
        c.t.start();

        System.out.println("Press Control-C to stop.");
    }
}

```

Although the **put()** and **get()** methods on **Q** are synchronized, nothing stops the producer from overrunning the consumer, nor will anything stop the consumer from consuming the same queue value twice. Thus, you get the erroneous output shown here (the exact output will vary with processor speed and task load):

```

Put: 1
Got: 1
Got: 1
Got: 1
Got: 1
Got: 1
Put: 2
Put: 3
Put: 4
Put: 5
Put: 6
Put: 7
Got: 7

```

As you can see, after the producer put 1, the consumer started and got the same 1 five times in a row. Then, the producer resumed and produced 2 through 7 without letting the consumer have a chance to consume them.

The proper way to write this program in Java is to use **wait()** and **notify()** to signal in both directions, as shown here:

```
// A correct implementation of a producer and consumer.
class Q {
    int n;
    boolean valueSet = false;

    synchronized int get() {
        while(!valueSet)
            try {
                wait();

            } catch(InterruptedException e) {
                System.out.println("InterruptedException caught");
            }

        System.out.println("Got: " + n);
        valueSet = false;
        notify();
        return n;
    }

    synchronized void put(int n) {
        while(valueSet)
            try {
                wait();
            } catch(InterruptedException e) {
                System.out.println("InterruptedException caught");
            }

        this.n = n;
        valueSet = true;
        System.out.println("Put: " + n);
        notify();
    }
}

class Producer implements Runnable {
    Q q;
    Thread t;

    Producer(Q q) {
        this.q = q;
        t = new Thread(this, "Producer");
    }

    public void run() {
        int i = 0;
```

```

        while(true) {
            q.put(i++);
        }
    }
}

class Consumer implements Runnable {
    Q q;
    Thread t;

    Consumer(Q q) {
        this.q = q;
        t = new Thread(this, "Consumer");
    }

    public void run() {
        while(true) {
            q.get();
        }
    }
}

class PCFixed {
    public static void main(String[] args) {
        Q q = new Q();
        Producer p = new Producer(q);
        Consumer c = new Consumer(q);

        // Start the threads.
        p.t.start();
        c.t.start();

        System.out.println("Press Control-C to stop.");
    }
}

```

Inside **get()**, **wait()** is called. This causes its execution to suspend until **Producer** notifies you that some data is ready. When this happens, execution inside **get()** resumes. After the data has been obtained, **get()** calls **notify()**. This tells **Producer** that it is okay to put more data in the queue. Inside **put()**, **wait()** suspends execution until **Consumer** has removed the item from the queue. When execution resumes, the next item of data is put in the queue, and **notify()** is called. This tells **Consumer** that it should now remove it.

Here is some output from this program, which shows the clean synchronous behavior:

```

Put: 1
Got: 1
Put: 2
Got: 2
Put: 3
Got: 3
Put: 4
Got: 4
Put: 5
Got: 5

```

Deadlock

A special type of error that you need to avoid that relates specifically to multitasking is *deadlock*, which occurs when two threads have a circular dependency on a pair of synchronized objects. For example, suppose one thread enters the monitor on object X and another thread enters the monitor on object Y. If the thread in X tries to call any synchronized method on Y, it will block as expected. However, if the thread in Y, in turn, tries to call any synchronized method on X, the thread waits forever, because to access X, it would have to release its own lock on Y so that the first thread could complete. Deadlock is a difficult error to debug for two reasons:

- In general, it occurs only rarely, when the two threads time-slice in just the right way.
- It may involve more than two threads and two synchronized objects. (That is, deadlock can occur through a more convoluted sequence of events than just described.)

To understand deadlock fully, it is useful to see it in action. The next example creates two classes, **A** and **B**, with methods **foo()** and **bar()**, respectively, which pause briefly before trying to call a method in the other class. The main class, named **Deadlock**, creates an **A** and a **B** instance, and then calls **deadlockStart()** to start a second thread that sets up the deadlock condition. The **foo()** and **bar()** methods use **sleep()** as a way to force the deadlock condition to occur.

```
// An example of deadlock.
class A {
    synchronized void foo(B b) {
        String name = Thread.currentThread().getName();

        System.out.println(name + " entered A.foo");

        try {
            Thread.sleep(1000);
        } catch (Exception e) {
            System.out.println("A Interrupted");
        }

        System.out.println(name + " trying to call B.last()");
        b.last();
    }

    synchronized void last() {
        System.out.println("Inside A.last");
    }
}

class B {
    synchronized void bar(A a) {
        String name = Thread.currentThread().getName();
        System.out.println(name + " entered B.bar");

        try {
            Thread.sleep(1000);
        } catch (Exception e) {
```



```

        System.out.println("B Interrupted");
    }

    System.out.println(name + " trying to call A.last()");
    a.last();
}

synchronized void last() {
    System.out.println("Inside B.last");
}
}

class Deadlock implements Runnable {
    A a = new A();
    B b = new B();
    Thread t;

    Deadlock() {
        Thread.currentThread().setName("MainThread");
        t = new Thread(this, "RacingThread");
    }

    void deadlockStart() {
        t.start();
        a.foo(b); // get lock on a in this thread.
        System.out.println("Back in main thread");
    }

    public void run() {
        b.bar(a); // get lock on b in other thread.
        System.out.println("Back in other thread");
    }

    public static void main(String[] args) {
        Deadlock dl = new Deadlock();

        dl.deadlockStart();
    }
}

```

When you run this program, you will see the output shown here, although whether **A.foo()** or **B.bar()** executes first will vary based on the specific execution environment.

```

MainThread entered A.foo
RacingThread entered B.bar
MainThread trying to call B.last()
RacingThread trying to call A.last()

```

Because the program has deadlocked, you need to press CTRL-C to end the program. You can see a full thread and monitor cache dump by pressing CTRL-BREAK on a PC. You will see that **RacingThread** owns the monitor on **b**, while it is waiting for the monitor on **a**. At the same time, **MainThread** owns **a** and is waiting to get **b**. This program will never complete. As this example illustrates, if your multithreaded program locks up occasionally, deadlock is one of the first conditions that you should check for.

Suspending, Resuming, and Stopping Threads

Sometimes, suspending execution of a thread is useful. For example, a separate thread can be used to display the time of day. If the user doesn't want a clock, then its thread can be suspended. Whatever the case, suspending a thread is a simple matter. Once suspended, restarting the thread is also a simple matter.

The mechanisms to suspend, stop, and resume threads differ between early versions of Java, such as Java 1.0, and more modern versions, beginning with Java 2. Prior to Java 2, a program used **suspend()**, **resume()**, and **stop()**, which are methods defined by **Thread**, to pause, restart, and stop the execution of a thread. Although these methods seem to be a perfectly reasonable and convenient approach to managing the execution of threads, they must not be used for new Java programs. Here's why. The **suspend()** method of the **Thread** class was deprecated by Java 2 several years ago. This was done because **suspend()** can sometimes cause serious system failures. Assume that a thread has obtained locks on critical data structures. If that thread is suspended at that point, those locks are not relinquished. Other threads that may be waiting for those resources can be deadlocked.

The **resume()** method is also deprecated. It does not cause problems, but cannot be used without the **suspend()** method as its counterpart.

The **stop()** method of the **Thread** class, too, was deprecated by Java 2. This was done because this method can sometimes cause serious system failures. Assume that a thread is writing to a critically important data structure and has completed only part of its changes. If that thread is stopped at that point, that data structure might be left in a corrupted state. The trouble is that **stop()** causes any lock the calling thread holds to be released. Thus, the corrupted data might be used by another thread that is waiting on the same lock.

Because you can't now use the **suspend()**, **resume()**, or **stop()** methods to control a thread, you might be thinking that no way exists to pause, restart, or terminate a thread. But, fortunately, this is not true. Instead, a thread must be designed so that the **run()** method periodically checks to determine whether that thread should suspend, resume, or stop its own execution. Typically, this is accomplished by establishing a flag variable that indicates the execution state of the thread. As long as this flag is set to "running," the **run()** method must continue to let the thread execute. If this variable is set to "suspend," the thread must pause. If it is set to "stop," the thread must terminate. Of course, a variety of ways exist in which to write such code, but the central theme will be the same for all programs.

The following example illustrates how the **wait()** and **notify()** methods that are inherited from **Object** can be used to control the execution of a thread. Let us consider its operation. The **NewThread** class contains a **boolean** instance variable named **suspendFlag**, which is used to control the execution of the thread. It is initialized to **false** by the constructor. The **run()** method contains a **synchronized** statement block that checks **suspendFlag**. If that variable is **true**, the **wait()** method is invoked to suspend the execution of the thread. The **mysuspend()** method sets **suspendFlag** to **true**. The **myresume()** method sets **suspendFlag** to **false** and invokes **notify()** to wake up the thread. Finally, the **main()** method has been modified to invoke the **mysuspend()** and **myresume()** methods.

```
// Suspending and resuming a thread the modern way.
class NewThread implements Runnable {
    String name; // name of thread
    Thread t;
```

```

boolean suspendFlag;

NewThread(String threadname) {
    name = threadname;
    t = new Thread(this, name);
    System.out.println("New thread: " + t);
    suspendFlag = false;
}

// This is the entry point for thread.
public void run() {
    try {
        for(int i = 15; i > 0; i--) {
            System.out.println(name + ": " + i);
            Thread.sleep(200);
            synchronized(this) {
                while(suspendFlag) {
                    wait();
                }
            }
        }
    } catch (InterruptedException e) {
        System.out.println(name + " interrupted.");
    }
    System.out.println(name + " exiting.");
}

synchronized void mysuspend() {
    suspendFlag = true;
}

synchronized void myresume() {
    suspendFlag = false;
    notify();
}
}

class SuspendResume {
    public static void main(String[] args) {
        NewThread ob1 = new NewThread("One");
        NewThread ob2 = new NewThread("Two");

        ob1.t.start(); // Start the thread
        ob2.t.start(); // Start the thread

        try {
            Thread.sleep(1000);
            ob1.mysuspend();
            System.out.println("Suspending thread One");
            Thread.sleep(1000);
            ob1.myresume();
            System.out.println("Resuming thread One");
            ob2.mysuspend();
            System.out.println("Suspending thread Two");
            Thread.sleep(1000);
        }
    }
}

```

```
        ob2.myresume();
        System.out.println("Resuming thread Two");
    } catch (InterruptedException e) {
        System.out.println("Main thread Interrupted");
    }

    // wait for threads to finish
    try {
        System.out.println("Waiting for threads to finish.");
        ob1.t.join();
        ob2.t.join();
    } catch (InterruptedException e) {
        System.out.println("Main thread Interrupted");
    }

    System.out.println("Main thread exiting.");
}
}
```

When you run the program, you will see the threads suspend and resume. Later in this book, you will see more examples that use the modern mechanism of thread control. Although this mechanism may not appear as simple to use as the old way, nevertheless, it is the way required to ensure that run-time errors don't occur. It is the approach that *must* be used for all new code.

Obtaining a Thread's State

As mentioned earlier in this chapter, a thread can exist in a number of different states. You can obtain the current state of a thread by calling the **getState()** method defined by **Thread**. It is shown here:

`Thread.State getState()`

It returns a value of type **Thread.State** that indicates the state of the thread at the time at which the call was made. **State** is an enumeration defined by **Thread**. (An enumeration is a list of named constants. It is discussed in detail in Chapter 12.) Here are the values that can be returned by **getState()**:

Value	State
BLOCKED	A thread that has suspended execution because it is waiting to acquire a lock.
NEW	A thread that has not begun execution.
RUNNABLE	A thread that either is currently executing or will execute when it gains access to the CPU.
TERMINATED	A thread that has completed execution.
TIMED_WAITING	A thread that has suspended execution for a specified period of time, such as when it has called sleep() . This state is also entered when a timeout version of wait() or join() is called.
WAITING	A thread that has suspended execution because it is waiting for some action to occur. For example, it is waiting because of a call to a non-timeout version of wait() or join() .

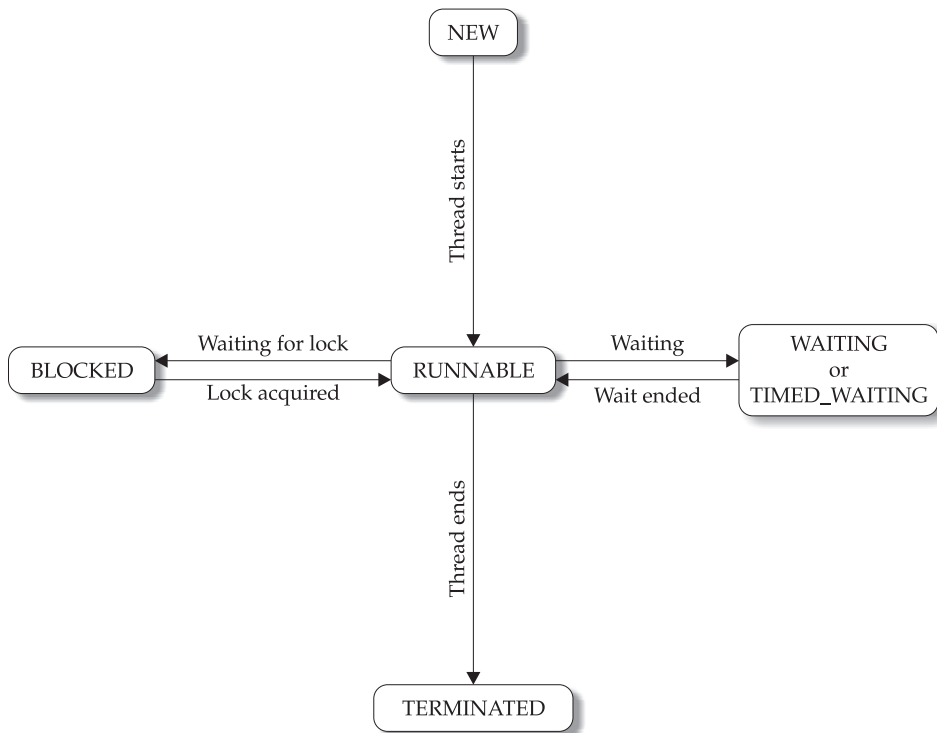


Figure 11-1 Thread states

Figure 11-1 diagrams how the various thread states relate.

Given a **Thread** instance, you can use `getState()` to obtain the state of a thread. For example, the following sequence determines if a thread called `thrd` is in the **RUNNABLE** state at the time `getState()` is called:

```
Thread.State ts = thrd.getState();

if (ts == Thread.State.RUNNABLE) // ...
```

It is important to understand that a thread's state may change after the call to `getState()`. Thus, depending on the circumstances, the state obtained by calling `getState()` may not reflect the actual state of the thread only a moment later. For this (and other) reasons, `getState()` is not intended to provide a means of synchronizing threads. It's primarily used for debugging or for profiling a thread's run-time characteristics.

Using a **Factory Method** to **Create and Start a Thread**

In some cases, it is not necessary to separate the creation of a thread from the start of its execution. In other words, sometimes it is convenient to create and start a thread at the same time. One way to do this is to use a static factory method. A *factory method* is a method that returns an object of a class. Typically, factory methods are *static* methods of a class. They are

used for a variety of reasons, such as to set an object to some initial state prior to use, to configure a specific type of object, or in some cases to enable an object to be reused. As it relates to creating and starting a thread, a factory method will create the thread, call **start()** on the thread, and then return a reference to the thread. With this approach, you can create and start a thread through a single method call, thus streamlining your code.

For example, assuming the **ThreadDemo** program shown near the start of this chapter, adding the following factory method to **NewThread** enables you to create and start a thread in a single step:

```
// A factory method that creates and starts a thread.
public static NewThread createAndStart() {
    NewThread myThrd = new NewThread();
    myThrd.t.start();
    return myThrd;
}
```

Using **createAndStart()**, you can now replace this sequence:

```
NewThread nt = new NewThread(); // create a new thread
nt.t.start(); // Start the thread
```

with

```
NewThread nt = NewThread.createAndStart();
```

Now the thread is created and started in one step.

In cases in which you don't need to keep a reference to the executing thread, you can sometimes create and start a thread with one line of code, without the use of a factory method. For example, again assuming the **ThreadDemo** program, the following creates and starts a **NewThread** thread:

```
new NewThread().t.start();
```

However, in real-world applications, you will usually need to keep a reference to the thread, so the factory method is often a good choice.

Using Multithreading

The key to utilizing Java's multithreading features effectively is to think concurrently rather than serially. For example, when you have two subsystems within a program that can execute concurrently, make them individual threads. With the careful use of multithreading, you can create very efficient programs. A word of caution is in order, however: If you create too many threads, you can actually degrade the performance of your program rather than enhance it. Remember, some overhead is associated with context switching. If you create too many threads, more CPU time will be spent changing contexts than executing your program! One last point: To create compute-intensive applications that can automatically scale to make use of the available processors in a multicore system, consider using the Fork/Join Framework, which is described in Chapter 29.